Intracranial pressure and promontory vibration with soft tissue stimulation in cadaveric human whole heads

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Abstract: HYPOTHESIS: Intracranial pressure and skull vibrations are correlated and depend on the stimulation position and frequency. BACKGROUND: A hearing sensation can be elicited by vibratory stimulation on the skin covered skull, or by stimulation on soft tissue such as the neck. It is not fully understood whether different stimulation sites induce the skull vibrations responsible for the perception or whether other transmission pathways are dominant. The aim of this study was to assess the correlation between intracranial pressure and skull vibration measured on the promontory for stimulation to different sites on the head. METHODS: Measurements were performed on four human cadaver heads. A bone conduction hearing aid was held in place with a 5-Newton steel headband at four locations (mastoid, forehead, eye, and neck). While stimulating in the frequency range of 0.3 to 10 kHz, acceleration of the cochlear promontory was measured with a Laser Doppler Vibrometer, and intracranial pressure at the center of the head with a hydrophone. RESULTS: Promontory acceleration and intracranial pressure was measurable for all stimulation sites. The ratios were comparable between all stimulation sites for frequencies below 2 kHz. CONCLUSION: These findings indicate that both promontory acceleration and intracranial pressure are involved for stimulation on the sites investigated. The transmission pathway of sound energy is comparable for the four stimulation sites.

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Intracranial Pressure and Promontory Vibration With Soft Tissue Stimulation in Cadaveric Human Whole Heads

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Hypothesis: Intracranial pressure and skull vibrations are correlated and depend on the stimulation position and frequency.
Background: A hearing sensation can be elicited by vibratory stimulation on the skin covered skull, or by stimulation on soft tissue such as the neck. It is not fully understood whether different stimulation sites induce the skull vibrations responsible for the perception or whether other transmission pathways are dominant. The aim of this study was to assess the correlation between intracranial pressure and skull vibration measured on the promontory for stimulation to different sites on the head.
Methods: Measurements were performed on four human cadaver heads. A bone conduction hearing aid was held in place with a 5-Newton steel headband at four locations (mastoid, forehead, eye, and neck). While stimulating in the frequency range of 0.3 to 10 kHz, acceleration of the cochlear promontory was measured with a Laser Doppler Vibrometer, and intracranial pressure at the center of the head with a hydrophone.
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Conclusion: These findings indicate that both promontory acceleration and intracranial pressure are involved for stimulation on the sites investigated. The transmission pathway of sound energy is comparable for the four stimulation sites. **Key Words:** Bone conduction—Intracranial pressure—Promontory—Soft tissue stimulation—Vibration.

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Bone conduction (BC) is an alternative pathway to air conduction (AC) for sound to reach the cochlea. It is widely used in clinical audiometry to determine hearing thresholds and differentiate between conductive and sensorineural hearing loss. However, the exact mechanism of BC hearing is not completely understood, either for normal hearing or in pathologic conditions of the middle ear. A complex interaction of several different pathways has been proposed as being responsible for the hearing sensation from BC stimulation: 1) compression and extension of the cochlear walls (1). 2) Inertia of cochlear fluid (2,3) and middle ear ossicles (2,4,5). 3) Radiation of sound pressure in the external ear canal, which is affected by changing the state of the ear canal from open to closed (occlusion effect) (6–8). 4) Dynamic sound pressure transmission from the skull interior (brain tissue and cerebrospinal fluid) to the cochlea. Sohmer and Freeman (9) coupled the cranial cavities of two experimental animals (fat sand rats) using a saline filled plastic tube. A BC click stimulus was applied to animal 1, while the auditory brainstem response (ABR) was recorded from the second animal. They found a correlation between stimulation in animal 1 and ABR response in animal 2 concluding that sound pressure can be transmitted by a fluid pathway to the cochlea and produce stimulation. In other experiments, acceleration of the bone was measured for stimulation to the forehead, eye, or directly on the brain. While ABR could be clearly recorded for all simulation sites, no acceleration of the bone was measured for stimulation to the eye in human (9) or to the brain in animals (10). By contrast, others have measured vibration on the teeth with stimulation to the eye (11). However, these investigators found no direct correlation between the BC hearing threshold and vibration of the teeth. It is not clear that the vibration of the teeth corresponds to the vibrations of the bone surrounding the cochlea. The importance and contributions of the different pathways may depend on the stimulation frequency. Additionally, the sites of stimulation, including on the bone, the skin covered bone, or soft tissue without contact to bone, should be further investigated (12).

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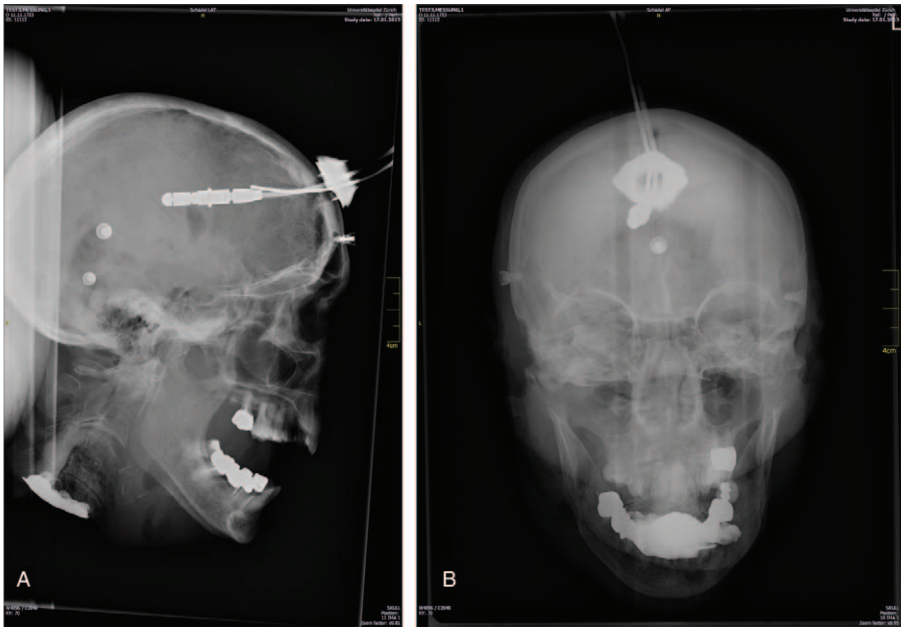

FIG. 1. The position of the hydrophone was checked by X-ray in two planes, lateral view (*A*), frontal view (*B*) to assure accurate positioning in the center of the cranial space, not touching the skull.

The aim of this study was to compare the relation between intracranial pressure and bone vibrations measured at the cochlear promontory for stimulation on skin covered bone (mastoid and forehead) and on soft tissue (eye and neck). We hypothesize that intracranial pressure and skull vibrations are correlated and depend on the stimulation position and frequency.

METHODS

The experiments were reviewed and approved by the institutional Ethic Committee (KEK-ZH-Nr. 2012-0136). Four cadaveric human whole heads that were conserved using a technique described by Thiel (13) were used. First, an endaural incision was performed between the helix and the tragus to achieve access to the promontory. Next, a tympanomeatal flap was elevated to expose the middle ear (14). Two self-retaining retractors were placed to allow good visualization of both the endaural surgery and the later LDV measurement. To enhance reflectivity of the laser beam, a small piece of retroreflective foil (1×1 mm) was placed on the measurement position located on the cochlear promontory near the round window. Details regarding the surgical preparations are described in our previous work (15). The skull was opened at the vertex and a tube of 10 mm diameter was tightly sealed to the opening.

The cadaver heads were supported on a soft gel head ring (Model 4006.0200, MAQUET Medical Systems, Wayne, NJ, U.S.A.), positioned on a stainless-steel table to decouple vibrations from external sources. A hydrophone (Type 8103; Brüel & Kjær, Nærum, Denmark) was inserted into the intracranial space through the tube. The hydrophone was positioned at the center of the cranial hemisphere and its position controlled by X-ray (Fig. 1), whereas care was taken to prevent any contact with the sample and minimize any direct mechanical coupling between the hydrophone and the skull. The physiologic intracranial pressure of 15 cm H_2O was maintained by a water column in the tube attached to the skull (16).

The transducer of a BAHA Cordell II (Cochlear Company, Sydney, Australia) was attached to the head at four positions (mastoid, forehead, eye, and neck) using a 5-Newton steel headband. The position on the mastoid corresponded to the position typically used in clinical audiometry. For the forehead, a position in the midline 5 cm above the root of the nose was chosen. When positioning the transducer on the eye, great care was taken to avoid touching the bone of the orbita while assuring that the whole surface of the transducer made contact with the vitreous body. For stimulation on the neck, the transducer was placed on the sternocleidomastoid muscle approximately 10 to 12 cm below its insertion on the mastoid. The coupling forces were controlled with a spring gauge (Light Line, Pesola, Switzerland). The stimulus was directly routed to the transducer with a stimulus intensity of 10 V, which was generated by the Audio Precision System One (Audio Precision, Inc., U.S.A., for Heads 1, 3, and 4) or the B&K data acquisition system Type 3052 (B&K, Incorp., Nærum, Denmark, for Head 2). The change of acquisition systems was dictated by availability at the time of each experiment. The sound stimulus consisted of a stepped sine measurement procedure in the frequency range of 0.3 to 10 kHz. The measurement frequencies were logarithmically spaced (50 frequency points per decade), resulting in 78 frequencies in the frequency range used.

All motions of the cochlear promontory were measured at a single point using an OFV-3001 Scanning Laser Doppler Vibrometry system (Polytec GmbH, Waldbronn, Germany). The sampling frequency was set at 51.2 kHz. The output of the Scanning Laser Doppler Vibrometry system was coupled to the Audio Precision System One (Heads 1, 3, and 4) or the B&K data acquisition system (Head 2) for further data processing. All of the measurement procedures were controlled by the AP 2700 Control software (Audio Precision, Inc.) for the Audio Precision System One and PULSE software for the B&K data acquisition system (Brüel & Kjær), with both softwares installed on a

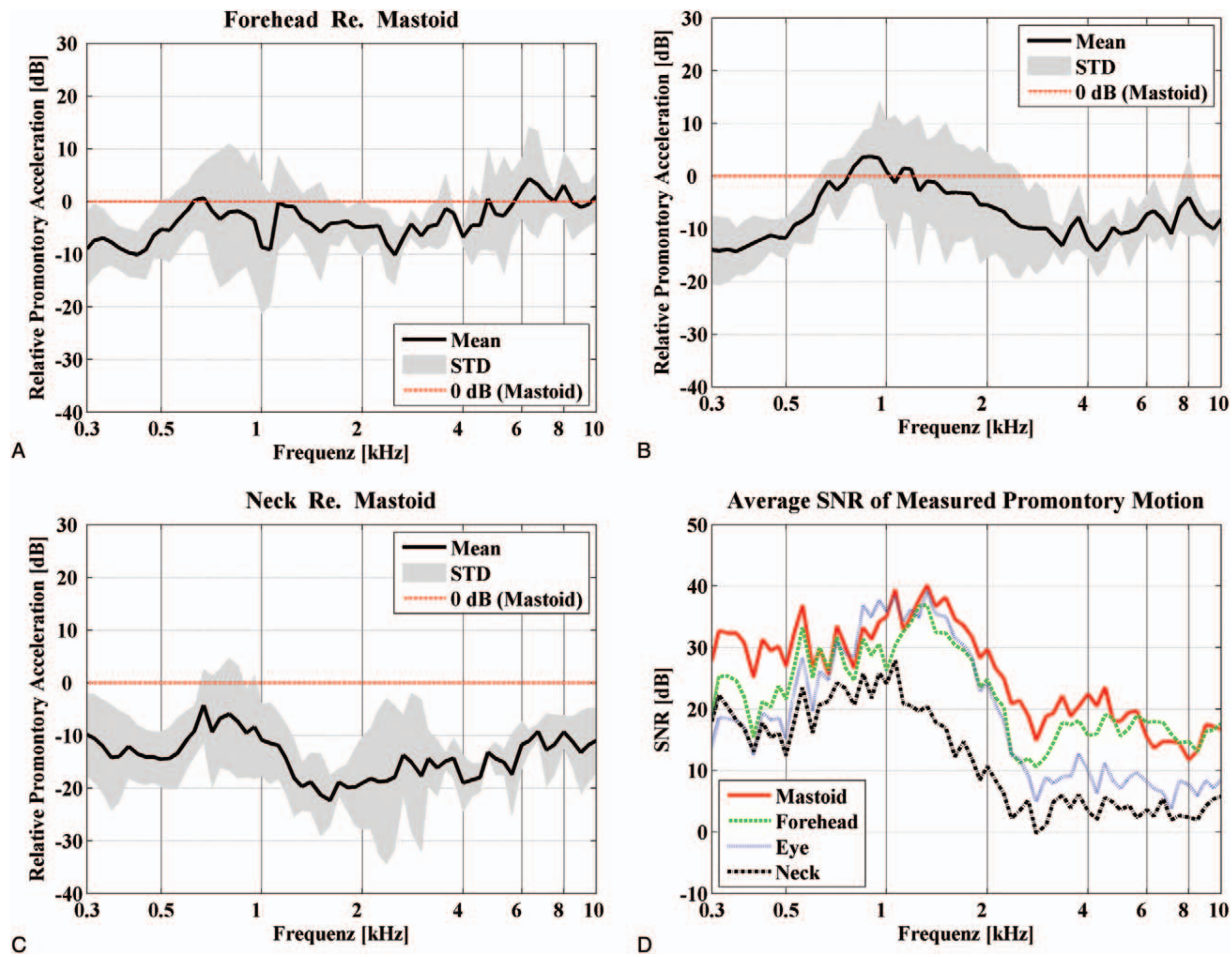

FIG. 2. Promontory acceleration with stimulations on the forehead (*A*), eye (*B*), and neck (*C*), relative to promontory acceleration with stimulations on the mastoid (0 dB corresponds to a ratio of 1). The signal-to-noise ratios (SNRs) of the measured promontory motions, averaged through the four cadaver heads, are shown in (*D*).

personal computer. The acceleration of the cochlear promontory was calculated from the recorded velocity. Simultaneously, intracranial pressure was recorded using the hydrophone positioned in the cranial space (see the above). The recorded pressures were routed to the data acquisition system via a charge amplifier (Type 2690-0S Low noise version, Brüel & Kjær).

RESULTS

To determine the relative differences between the stimulation locations (i.e. forehead, neck, and eye), cochlear promontory acceleration and intracranial pressure were normalized by the corresponding response with stimulation to the mastoid, for each cadaver head individually. The results were then averaged across samples.

Figure 2 displays the normalized promontory acceleration, including mean and standard deviation for stimulation on forehead (A), eye (B), and neck (C). The average signal-to-noise ratios (SNRs) of the measured cochlear promontory motions for the four stimulation positions are also shown in Figure 2D. For stimulation to the forehead, the average SNR was greater than 10 dB along the considered frequency range (Fig. 2D). There was a tendency for low SNR for stimulation to the neck at frequencies above 2 kHz and for stimulation to the eye for frequencies above 3 kHz. Generally, the normalized acceleration of the cochlear promontory was largest for stimulation to the forehead, showing an average gain of -5 dB at 0.3 to 4 kHz and 2 dB above 4 kHz, relative to stimulation to the mastoid. The lowest normalized acceleration of the promontory was measured for stimulation to the neck showing an average gain of -10 dB at 0.3 to 1 kHz and -15 dB above 1 kHz.

Similarly, intracranial pressure for stimulation at all sites was measured in all four specimens, and pressure measurements for stimulation to the forehead, eye, and neck were normalized relative to pressure measurements for stimulation to the mastoid. For each normalized intracranial pressure, the mean and standard deviation across all heads were calculated. Results are displayed in Figure 3 (A, stimulation on forehead; B, stimulation on eye; C, stimulation on neck).

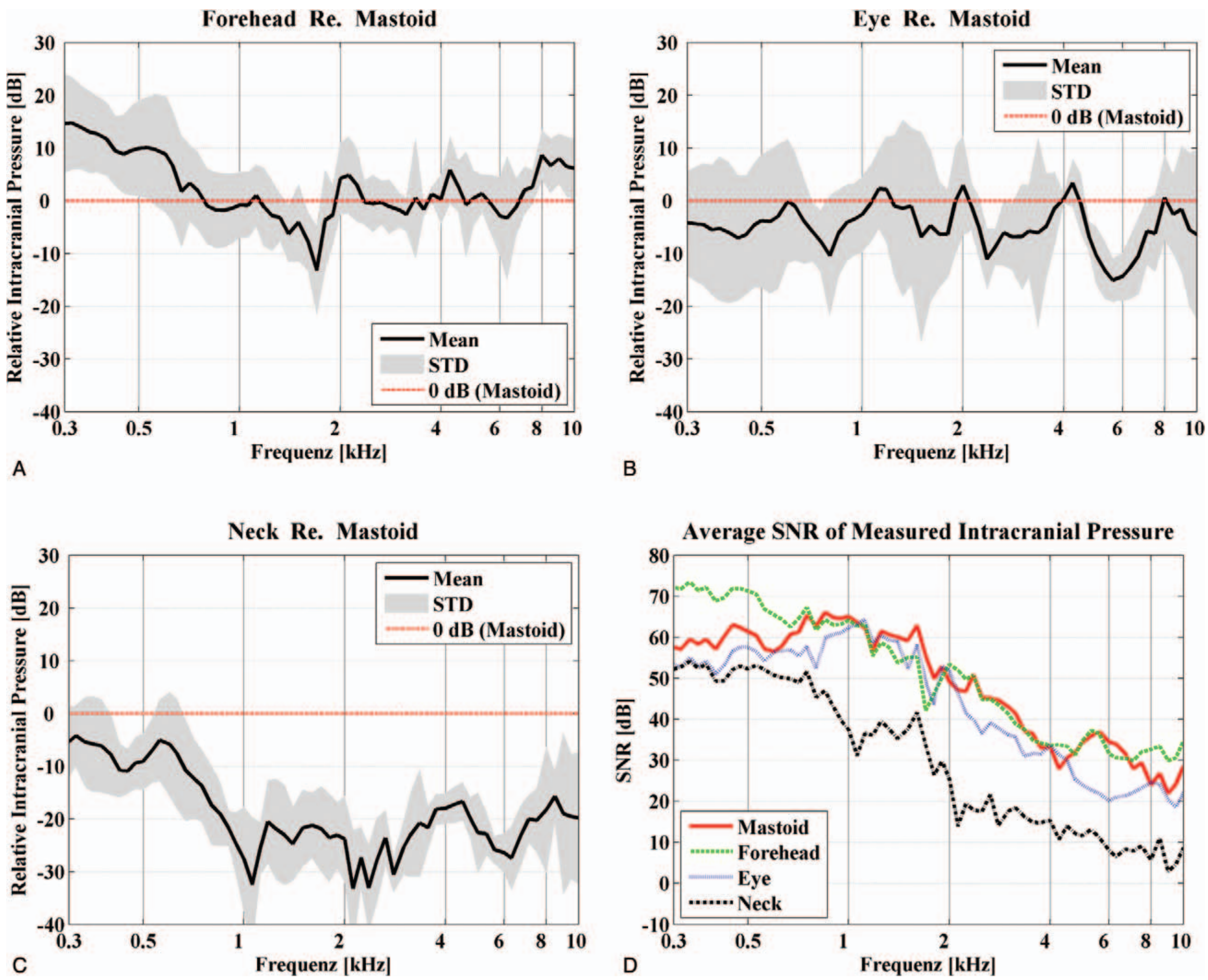

FIG. 3. Intracranial pressure with stimulations on the forehead (*A*), eye (*B*), and neck (*C*), relative to intracranial pressure with stimulations on the mastoid (0 dB corresponds to a ratio of 1). The signal-to-noise ratios (SNRs) of the measured intracranial pressure, averaged through the four cadaver heads, are shown in (*D*).

Average SNRs greater than 20 dB were achieved for stimulation to the mastoid, forehead, and eye for the full measurement frequency range (Fig. 3D). The average SNR was less than 10 dB above 6 kHz for stimulation to the eye. Generally, the largest normalized intracranial pressure was measured for stimulation to the forehead, showing an average gain of 10 dB at 0.3 to 0.6 kHz and 2 dB above 2 kHz. Lowest normalized intracranial pressure was measured for stimulation to the neck showing an average gain of -7 dB at 0.3 to 0.6 kHz and -25 dB above 1 kHz.

The ratio between vibration of the cochlear promontory (Fig. 2) and intracranial pressure (Fig. 3) for stimulation to the forehead, eye, and neck relative to the mastoid was calculated in all four heads individually. For each relative ratio, the mean and standard deviation across all heads was calculated, and the results are presented in Figure 4. For all stimulation locations the relative ratio increases significantly (i.e., $\sim$20–25 dB) with frequency in the range of 0.2 to 1 kHz. The relative ratios for stimulation to the neck and eye need to be interpreted with care for frequencies above 2 and 3 kHz, respectively, because the corresponding promontory motions were close to the noise level. For frequencies below 2 kHz, these findings indicate that regardless of the site of stimulation, vibration of the cochlear promontory and intracranial pressure was measured reliably. These two components seem to be related and are not mutually independent. The larger magnitude of the normalized cochlear promontory vibration and intracranial pressure (Figs. 2 and 3) when the stimulation is on the skin covered bone to the forehead, indicates that this stimulation mode is more efficient than stimulating on the eye or neck.

DISCUSSION

This study investigated the relation between vibration of the skull measured at the cochlear promontory and intracranial pressure for stimulation by a BC transducer

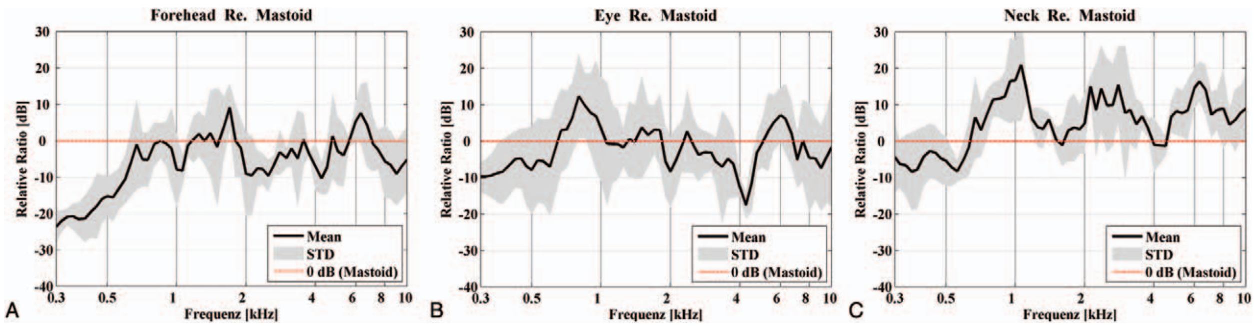

FIG. 4. Ratio of promontory motion (shown in Fig. 2) to intracranial pressure (shown in Fig. 3) with stimulations on the forehead (*A*), eye (*B*), and neck (*C*), relative to the corresponding ratio with stimulations on the mastoid.

at four different positions: mastoid, forehead, eye, and neck. Measurements were performed in four cadaveric whole heads that gave a close approximation to the in vivo condition for the following reasons: the heads were stored according to a technique described by Thiel (13), in which there was no significant difference in biomechanical testing as compared with fresh frozen material (17,18). For measurements on BC pathways, dry skulls, temporal bones, and animals have been used in previous studies (4,5,9,19). Using cadaveric whole heads has the advantage of the presence of soft tissue remaining attached to the head and a fluid filled intracranial space as compared with measurements on dry skulls or temporal bones. Additionally, the presence of the whole circumference of the head may model the complexity of BC pathways more adequately than temporal bones or measurements on animals.

The absolute values of the cochlear promontory vibrations are comparable to the measurements reported by others who stimulated on the skin covered bone on Thiel fixed heads (18), directly on the skull (20), or on skin covered bone on live human subjects (21). In Figure 5, the promontory accelerations with the steel headband used in this study (i.e., Heads 1–4) were normalized by the stimulation force to make comparisons with the promontory responses to force stimulation from a transducer screwed into the skull of cadaver heads (20) and mounted by a headband in live human subjects (21). The stimulation forces with the BAHA Cordell II transducer placed on the mastoid by the steel headband were estimated from measurements using an artificial mastoid (Type 4930, Brüel & Kjær). During the measurement of the stimulation force, the mechanical impedance of the artificial mastoid was measured, and the static force between the transducer and the surface of the artificial mastoid was maintained at approximately 5 Newton, which corresponds to the coupling force between the skin and the transducer in the cadaver heads. The cochlear promontory acceleration for stimulation to the mastoid showed approximately 7 dB standard deviation on average across four cadaver heads along the measured frequency range, which is in agreement with previous bone conduction studies in cadaver heads (18).

Vibrations of the promontory motion were only measured in one direction, which does not address precisely the complexity of the three-dimensional motion of the skull in BC stimulation. Cochlear promontory vibration levels in the three perpendicular directions are normally within 5 dB for frequencies above 1 kHz, whereas they can be greater (by up to 20 dB) in the direction of stimulation for frequencies below 1 kHz (22). This can explain why promontory vibration is largest for stimulation to the mastoid below 1 kHz, because the mastoid stimulation is in line with the direction of laser measurement, whereas stimulation on the forehead is perpendicular to it. Above 1 kHz, promontory motion is comparable for all stimulation sites (Fig. 2).

One limitation of our measurements is that some data were close to, or below, the noise level, especially for stimulation at frequencies above 4 kHz and for stimulation to the neck and eye. One reason is the damping of the skin that affects the effective stimulation at

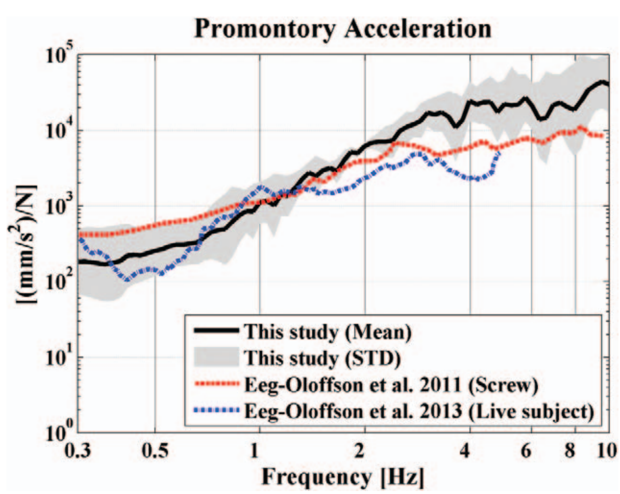

FIG. 5. Magnitude of promontory motion from the four cadaver heads in this study, in comparison with magnitude of promontory motion with direct stimulation on the skull bone of the cadaver heads (20, averaged from 4 cadaver heads) and stimulation using a headband in live human subjects (21, averaged from 16 subjects). The magnitudes of the promontory motions were normalized by the stimulation forces, which were estimated from measurements using an artificial mastoid.

frequencies above 4 kHz (23). A greater driving voltage of the transducer could have been used but most likely would have caused distortion of the stimulation. To investigate possible electrical or acoustic interference between the BAHA and the hydrophone, a separate set of measurements was conducted, where a stimulation signal was applied to the BAHA whereas it was supported without direct mechanical contact with the cadaver head. The corresponding hydrophone response was 20 to 40 dB lower, in the range of 0.2 to 4 kHz, relative to the lowest recorded response in the case when the BAHA was in contact with the cadaver heads (i.e., with stimulation to the neck, Fig. 3C). Above 4 kHz, there was no noticeable response of the hydrophone above its noise floor (i.e., no excitation by the BAHA). This indicates that any possible electrical or acoustic interference between the BAHA and the hydrophone was insignificant, and did not affect the hydrophone measurements by mechanical contact or any of the corresponding observations and conclusions.

There was large variability in the absolute values of the measured quantities among the four heads. However, normalization of the data of each stimulation location relative to stimulation to the mastoid reduced this variability and allowed for averaging of the measurements of all four cadaver heads. The exact reason for this large variability is unclear. One reason might be differences in anatomical structures such as thickness and circumference of the skull, or thickness and structure of the soft tissue. Another possible contributor to the differences is the coupling and attenuation of the skin and soft tissues in the transducer–skull interface although this influence was minimized by controlling the static force of the coupling of the headband by a force gauge.

It has been shown that direct stimulation of the soft tissues (i.e., eye or neck) stimulates the cochlea and causes a hearing sensation (11,24,25). In the current measurements, the gain for both the cochlear promontory vibration and intracranial pressure tended to be below 0 dB for stimulation to the eye and neck, relative to stimulation to the mastoid. Such findings are consistent with poorer hearing thresholds for stimulation at these locations as compared with stimulation to the mastoid. The lower gain of promontory vibration, down to −10 dB, for stimulation to the eye compared with stimulation to the mastoid is consistent with the 10 to 15 dB lower hearing thresholds for stimulation to the eye (11,26).

The results presented in this study indicate that the relative ratio of the cochlear promontory vibration and intracranial pressure is comparable (i.e., within 10 dB) for stimulation on skin covered bone and soft tissue without direct contact to bone, meaning that transmission pathways do not show large differences in the measured frequency range. These findings can be explained by an interaction between soft tissue, skull contents, and skull that results in vibration of the bone surrounding the cochlea and the intracranial space. It is controversially discussed in the literature whether or not vibration of the soft tissue is independent of bone vibration. Some reports claim that soft tissue conduction does not involve bone vibration (9,10,25,27). In an animal model, Chordekar et al. (25) measured ABR and vibrations of the bony vestibule with an LDV for BC and soft tissue stimulation. For BC stimulation, ABR and bone vibrations were measured, whereas for soft tissue stimulation only ABR was recorded for low intensities. One possible reason for the difference with our findings is that the vibrations may have been too low to be detected, because low-intensity stimulation was used. If bone vibration did not contribute to BC hearing for stimulation to the neck, then the relative ratio between promontory vibration and intracranial pressure is expected to be much lower. Our data, as shown in Figure 4, do not show such a difference in ratio, suggesting that soft tissue stimulation involves bone vibration similarly to direct stimulation on the bone.

CONCLUSIONS

The similarities in the ratio between promontory vibration and intracranial pressure for stimulation on bone and soft tissue indicate that all investigated stimulation sites excite the cochlear walls and the intracranial fluid to a similar extent, which means that bone vibration is involved in soft tissue stimulation.

REFERENCES

1. Tonndorf J. Compressional bone conduction in cochlear models. *J Acoust Soc Am* 1962;34:1127–31.
2. Wever EG, Lawrence M. *Physiological Acoustics*. Princeton, NJ: Princeton University Press; 1954.
3. Stenfelt S, Goode RL. Bone-conducted sound: Physiological and clinical aspects. *Otol Neurotol* 2005;26:1245–61.
4. Barany E. A contribution to the physiology of bone conduction. *Acta Otolaryngol* (Suppl 26):1938;1–223.
5. Stenfelt S, Hato N, Goode RL. Factors contributing to bone conduction: The middle ear. *J Acoust Soc Am* 2002;111:947–59.
6. Tonndorf J. Bone conduction. In: Tobias JV, editor. *Foundations of Auditory Theory, vol. II*. New York: Academic Press; 1972. pp. 197–237.
7. Khanna SM, Tonndorf J, Queller JE. Mechanical parameters of hearing by bone conduction. *J Acoust Soc Am* 1976;60:139–54.
8. Stenfelt S, Reinfeldt S. A model of the occlusion effect with bone conduction stimulation. *Int J Audiol* 2007;46:595–608.
9. Sohmer H, Freeman S. Further evidence for a fluid pathway during bone conduction auditory stimulation. *Hear Res* 2004;193:105–10.
10. Freeman S, Sichel JY, Sohmer H. Bone conduction experiments in animals: Evidence for a non-osseous mechanism. *Hear Res* 2000;146:72–80.
11. Ito T, Röösli C, Kim CJ, Sim JH, Huber AM, Probst R. Bone conduction thresholds and skull vibration measured on the teeth during stimulation at different sites on the human head. *Audiol Neurootol* 2011;16:12–22.
12. Perez R, Adelman C, Chordekar S, Ishai R, Sohmer H. Air, bone and soft tissue excitation of the cochlea in the presence of severe impediments to ossicle and window mobility. *Eur Arch Otorhinolaryngol* 2015;272:853–60.
13. Thiel W. [The preservation of the whole corpse with natural color.]. *Ann Anat* 1992;174:185–95.
14. Fisch U, May J, Linder T. *Tympanoplasty, Mastoidectomy and Stapes Surgery, 2nd 235 ed*. Stuttgart, Germany: Georg Thieme Verlag; 2008. 8–11.

15. Huber AM, Sim JH, Xie YZ, Chatzimichalis M, Ullrich O, Röösli C. The Bonebridge: Preclinical evaluation of a new transcutaneously-activated bone anchored hearing device. *Hear Res* 2013;301:93–9.
16. Steiner LA, Andrews PJ. Monitoring the injured brain: ICP and CBF. *Br J Anaesth* 2006;97:26–38.
17. Boryor A, Hohmann A, Wunderlich A, et al. In-vitro results of rapid maxillary expansion on adults compared with finite element simulations. *J Biomechan* 2010;43:1237–42.
18. Guignard J, Stieger C, Kompis M, Caversaccio M, Arnold A. Bone conduction in Thiel-embalmed cadaver heads. *Hear Res* 2013;306: 115–22.
19. Stenfelt S, Wild T, Hato N, Goode RL. Factors contributing to bone conduction: The outer ear. *J Acoust Soc Am* 2003;113:902–13.
20. Eeg-Olofsson M, Stenfelt S, Granström G. Implications for contralateral bone-conducted transmission as measured by cochlear vibrations. *Otol Neurotol* 2011;32:192–8.
21. Eeg-Olofsson M, Stenfelt S, Taghavi H, et al. Transmission of bone conducted sound—correlation between hearing perception and cochlear vibration. *Hear Res* 2013;306:11–20.
22. Stenfelt S, Goode RL. Transmission properties of bone conducted sound: Measurements in cadaver heads. *J Acoust Soc Am* 2005;118:2373–91.
23. Stenfelt SP, Hakansson BE. Sensitivity to bone conducted sound: excitation of the mastoid vs the teeth. *Scand Audiol* 1999;28:190–8.
24. Watanabe T, Bertoli S, Probst R. Transmission pathways of vibratory stimulation as measured by subjective thresholds and distortion-product otoacoustic emissions. *Ear Hear* 2008;29:667–73.
25. Chordekar S, Kriksunov L, Kishon-Rabin L, Adelman C, Sohmer H. Mutual cancellation between tones presented by air conduction, by bone conduction and by non-osseous (soft tissue) bone conduction. *Hear Res* 2012;283:180–4.
26. Adelman C, Sohmer H. Thresholds to soft tissue conduction stimulation compared to bone conduction stimulation. *Audiol Neurootol* 2013;18:31–5.
27. Perez R, Adelman C, Sohmer H. Bone conduction activation through soft tissues following complete immobilization of the ossicular chain, stapes footplate and round window. *Hear Res* 2011;280:82–5.